STAR QM08 Highlights II: STAR results on medium properties and response of the medium to energetic partons

Bedangadas Mohanty (for STAR Collaboration)

1) Introduction

After the discovery of the phenomenon of jet quenching at RHIC, the focus has been to study the properties of the medium formed in heavy ion collisions at high energy [1]. The basic approach has been to use the highly energetic partons available in the initial stages of the collisions as a probe for the properties of the subsequent medium that is formed. These partons then fragment into jets of hadrons and we look for modification to the properties of these jets. This is mostly done at RHIC by comparing the various experimental observations in p+p, d+Au and Au+Au collisions. The properties of the medium which we would like to study includes, the energy density achieved in the collisions, velocity of the sound in the medium, possible insights into partonic interactions and the mechanism of energy loss of the partons, collectivity, possibility of achieving thermalization and the effect of the medium on the mechanism of particle production. Correlations between the produced particles in the heavy ion collisions can be used as an experimental tool to address these issues. The study of the medium through high p_T triggered correlations is the main theme of this article. However only a few selected topics are covered in this article : (a) Parton energy loss in the medium formed in heavy ion collisions : Discussion on experimental data that can provide insights into theoretically expected difference in quark and gluon energy loss and measurements that can provide constraints on mechanism of parton energy loss, (b) Response of the medium to passage of energetic partons through it : Experimental data on observation of conical emission and ridge formation in heavy ion collisions. For further references please look at
STAR presentations at Quark Matter 2008 and available at http://www.star.bnl.gov/STAR/presentations/ .

2) Parton energy loss in the medium formed in heavy ion collisions

The non-Abelian feature of quantum chromodynamics (QCD) results in the gluons losing more energy than quarks in the medium formed in high energy heavy-ion collisions. Experimental results in p+p collisions when compared to NLO pQCD calculations show that at high transverse momentum (p_T) the produced protons+anti-protons are dominantly from gluon jets and charged pions have substantial contribution from quark jets. If such a scenario is applied to heavy-ion collisions at RHIC, one would expect the difference in quark and gluon energy loss to have an effect on measured observables, such as high p_T anti-proton/proton ratio and the nuclear modification factor for various charged pions and protons+anti-protons.

Figure 1 : Left panel – anti-proton/proton ratio in central 0-12% Au+Au,

minimum bias d+Au and p+p collisions at 200 GeV. The results are compared to model calculations without energy loss (dashed line) as expected for p+p collisions and with the color factor effects in energy loss in Au+Au collisions at 200 GeV.
Right panel – Nuclear Modification Factor for charged pions and proton+anti-protons in central Au+Au collisions at 200 GeV as a function transverse momentum of the hadron.

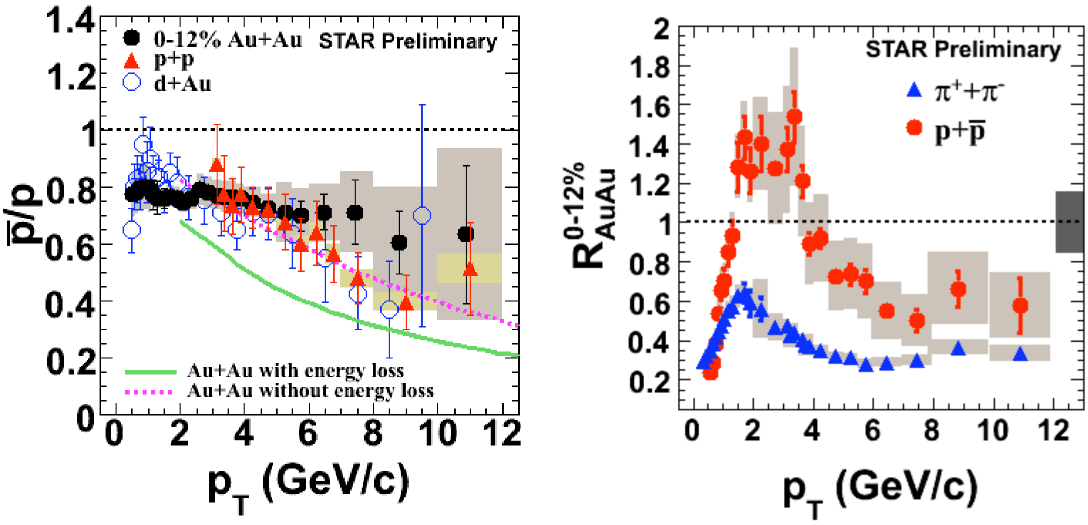
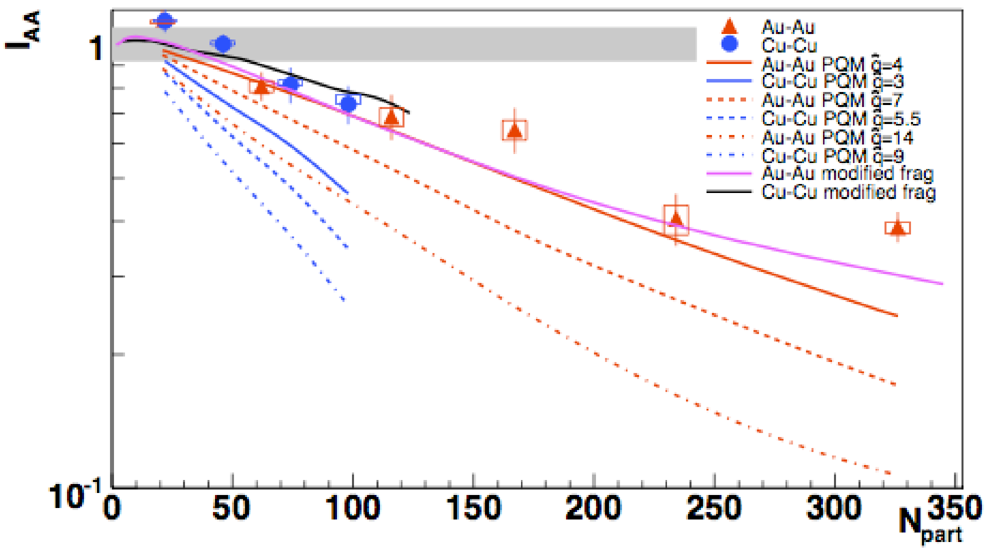


Figure 1 (left) shows the anti-proton/proton ratio for central Au+Au collisions at 200 GeV from STAR at high p_T (> 6 GeV/c) is comparable or slightly higher than the p+p and d+Au results [2]. This is in contrast to the naïve expectations from color charge dependence of energy loss, where the ratio at high p_T in Au+Au collisions are expected to be lower than p+p collisions. Comparison to model calculations without energy loss are in reasonable agreement with the p+p and d+Au results, whereas calculations including color charge dependence of energy loss [3] give a much lower value of the anti-proton/proton ratio compared to data for most of the measured p_T range. The stronger coupling of the gluons with the medium formed in Au+Au collisions expected to lead to a lower value of the nuclear modification factor (R_{AA}) an experimental observable that reflects parton energy loss. Figure 1 (right) shows the R_{AA} for proton+anti-proton (expected to be dominantly from gluons) is comparable or slightly higher than for charged pions (expected to have substantial contribution from quarks) at high p_T (> 6 GeV/c) for central Au+Au collisions at 200 GeV. This is in contrast to the naive expectation of a lower R_{AA} for proton+anti-protons compared to charged pions .

Although the nuclear modification factor for produced particles reflects the energy loss of partons in the medium formed in heavy-ion collisions, they were found to have a limited sensitivity to different mechanisms of partonic energy loss in the medium [4]. It was suggested that looking at di-hadron correlations can provide more sensitivity to properties of the medium [5]. In STAR we have carried a systematic study of di-hadron correlations with various collision species at different beam energies as a function of collision centrality. One such result of I_{AA} is shown in the figure 2 for 200 GeV Au+Au and Cu+Cu collisions as a function of collision centrality defined in terms of number of participating nucleons (N_{part}). The I_{AA} is defined as the integrated yield of the away-side associated particles per high p_T trigger scaled by the yield measured in d+Au collisions. The I_{AA} is similar for Au+Au and Cu+Cu collisions for systems with similar N_{part}. Comparison to theoretical calculations suggest that, our data rules out predictions from Parton Quenching Model [6] and while the model based on modified fragmentation [5] seems to do better.

Figure 2 : The ratio of integrated yield of the away-side associated particles per high p_T trigger in Au+Au and Cu+Cu collisions at 200 GeV scaled by the corresponding yields measured in d+Au collisions plotted as a function of number of participating nucleons. The results are compared to parton quenching model calculations (blue and red lines) and modified fragmentation model calculations (magenta and black lines).



It was further suggested that studying γ-hadron correlations would be more sensitive to the different mechanisms of partonic energy loss and also provide the full accounting of the jet energy loss [4].

Figure 3 : The ratio of integrated yield of the away-side associated particles per high p_T γ-trigger (left panel) and π^0-trigger (right panel) in Au+Au collisions at 200 GeV scaled by the corresponding yields measured in p+p collisions at 200 GeV, plotted as a function of number of participating nucleons. The results are shown for various $p_{T,assoc}$ ranges and compared to theoretical calculations.

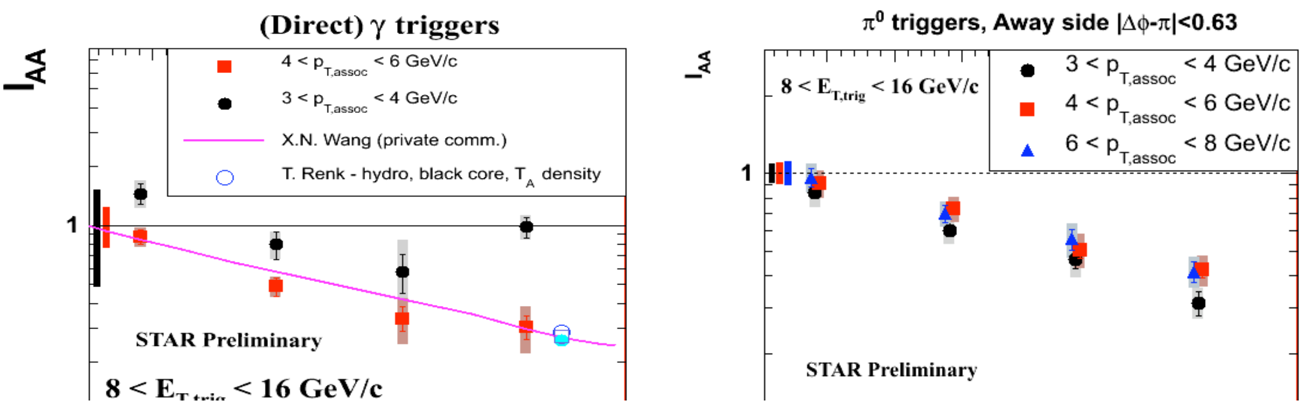


Figure 3 (left) shows the ***first measurements*** of I_{AA} from γ-hadron correlations in STAR as a function of number of participating nucleons in Au+Au collisions at 200 GeV. The I_{AA} shown in the figure is defined as the integrated yield of the away-side associated particles per direct photon trigger scaled by the yield measured in p+p collisions as a function of centrality. The results for γ-triggers are with $8 < E_T < 16$ GeV/c and the associated hadrons giving $3 < p_{T,assoc} < 4$ GeV/c and $4 < p_{T,assoc} < 6$ GeV/c ranges. Figure 3 (right) shows the I_{AA} with π^0 triggers. The I_{AA} values < 1 for central collisions supports the earlier picture of jet quenching at RHIC. This is just the beginning of the program with γ-hadron correlations. With future luminosities at RHIC II, we will be sensitive at the level to distinguish theoretical mechanisms. Within the current uncertainty the I_{AA} agrees with the theoretical calculations [4,7].

3. Response of the medium to the passage of energetic partons

It has been previously reported at RHIC, that on the away side of a high p_T trigger particle the correlated yields are strongly suppressed at $p_T > 2$ GeV/c, while at lower p_T the yield is enhanced [8]. Further in the away side the correlated hadrons appear to be partially equilibrated with the bulk medium and the distributions are broader (sometimes double peaked) in azimuth [9]. Identifying the underlying physics mechanism for such observations, one of which could be due to Mach cone shock-waves being generated by a large energy deposition in a hydrodynamic medium [10], can provide important information about properties of the medium, such as the speed of sound and equation of state. 3-particle azimuthal correlations between a high p_T trigger particle and two associated particles has the ability to discriminate the different underlying physics mechanisms.

Figure 4 : 3-particle correlations in azimuthal angle for minimum bias d+Au collisions (left panel) and 0-12% central Au+Au collisions at 200 GeV.

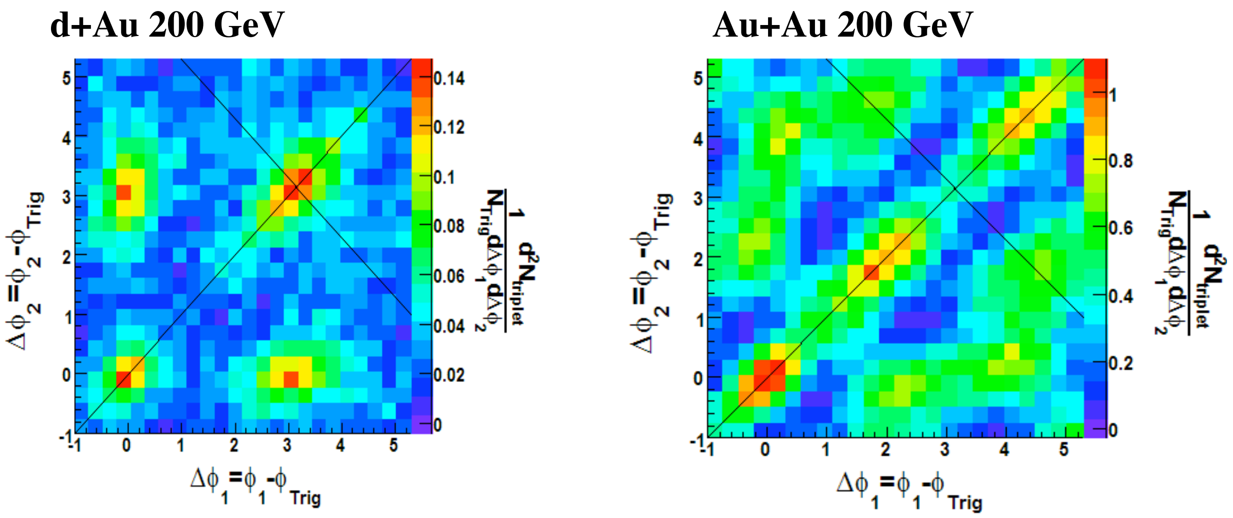
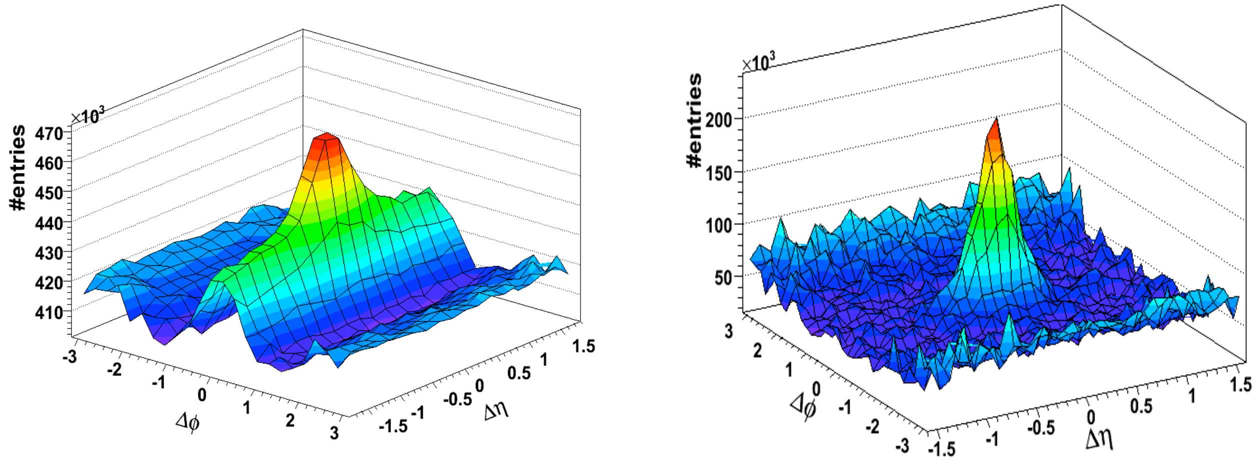


Figure 4 shows the background subtracted 3-particle azimuthal angle correlations in minimum bias d+Au (left) and 0-12% central Au+Au (right) collisions at 200 GeV from STAR. The trigger particles are in the range 3 – 4 GeV/c in p_T and associated particles in the range 1- 2 GeV/c in p_T. The analysis assumes the event to be composed of two components, one that is correlated with the trigger and the other is background, uncorrelated with the trigger except the indirect correlations via anisotropic flow. In Au+Au collisions we observe that opposite to the trigger particle in azimuth, the associated particles seem to populate preferentially on a cone around π radians, being equally far apart and symmetric about π and close together. Distinct peaks around angles of ~ 1.4 radians (cone angle) away from π are only observed in Au+Au collisions and not in d+Au. It may be noted that in d+Au system neither a large partonic energy deposition is observed nor the medium is expected to show substantial collectivity. These additional structures in Au+Au collisions are clear experimental evidence of conical emission of correlated hadrons with high p_T particles. Further we observe that the cone angle is independent of collision centrality and the associated particle p_T, indicating that the conical emission may not due to Cerenkov gluon radiation in central heavy-ion collisions. A separate analysis in STAR based on 3-particle cummulants [11] however has so far not seen a clear evidence of such a conical emission.

Studies of near-side di-hadron correlations ($\Delta\phi \sim 0$) at high $p_T > 6$ GeV/c revealed a jet-like correlation at small pair phase space separation ($\Delta\phi \sim 0$, $\Delta\eta \sim 0$) which is unmodified in central Au+Au collisions relative to d+Au, suggesting that the dominant production mechanism is jet fragmentation outside the dense medium. At lower momentum, significant correlated yield has been observed in central collisions at large pair separation in pseudorapidity $\Delta\eta$ (***the ridge***) (Figure 5 – observed in Au+Au (left) collisions and not in d+Au (right) collisions) [9,12].

Figure 5 : Di-hadron correlations between associated particle and high p_T trigger particle in azimuthal angle and pseudorapidity for Au+Au collisions (left panel) and d+Au collisions (right panel) at 200 GeV. The elongated structure along $\Delta\eta$ observed in Au+Au collisions is termed as the ridge.

Au+Au 200 GeV **d+Au 200 GeV**



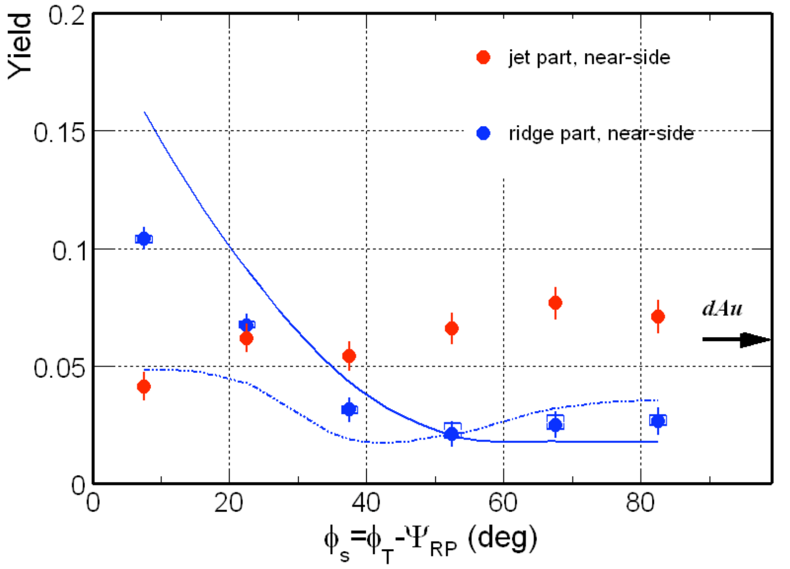
However, inclusive hadron production at moderate $p_T < 6$ GeV/c in central Au+Au collisions differs significantly from p+p and d+Au collision systems, and jet fragmentation may not be the dominant hadron production mechanism in this region [2]. It is therefore an open question whether the ridge is a novel manifestation of partonic energy loss [13] or is due to a different, non-perturbative mechanism such as recombination [14]. In order to provide further experimental inputs for deciphering the mechanism for ridge formation, STAR reported at the QM2008 several new results and only some of which are discussed below.

Based on experimental observations, we have assumed that the near-side projection onto $\Delta\eta$ can be separated into a jet-like peak centered at $\Delta\eta \sim 0, \Delta\phi \sim 0$ and an independent ridge component. Then we have studied the properties of various observables in these two components which are tabulated below.

Observable	Observation in ridge	Observation in jet
Slope of p_T spectra	$T_{Ridge} \sim T_{inclusive}$	$T_{jet} > T_{inclusive}$
Yields per trigger	Increases with N_{part}	Constant with N_{part}
Particle ratios	Like inclusive	Smaller than inclusive
Energy dependence of the yields	Observed in both 200 and 62.4 GeV Au+Au collisions, yields per trigger smaller in 62.4 GeV compared to 200 GeV	Yields per trigger smaller in 62.4 GeV compared to 200 GeV Ridge/Jet ratio similar for Au+Au collisions at 200 and 62.4 GeV
System-size dependence of the yields	Similar N_{part} yields similar in Au+Au and Cu+Cu collisions at a given beam energy	For similar N_{part} yields similar in Au+Au and Cu+Cu at a given beam energy
Trigger particle type dependence of the yields	No significant dependence	No significant dependence

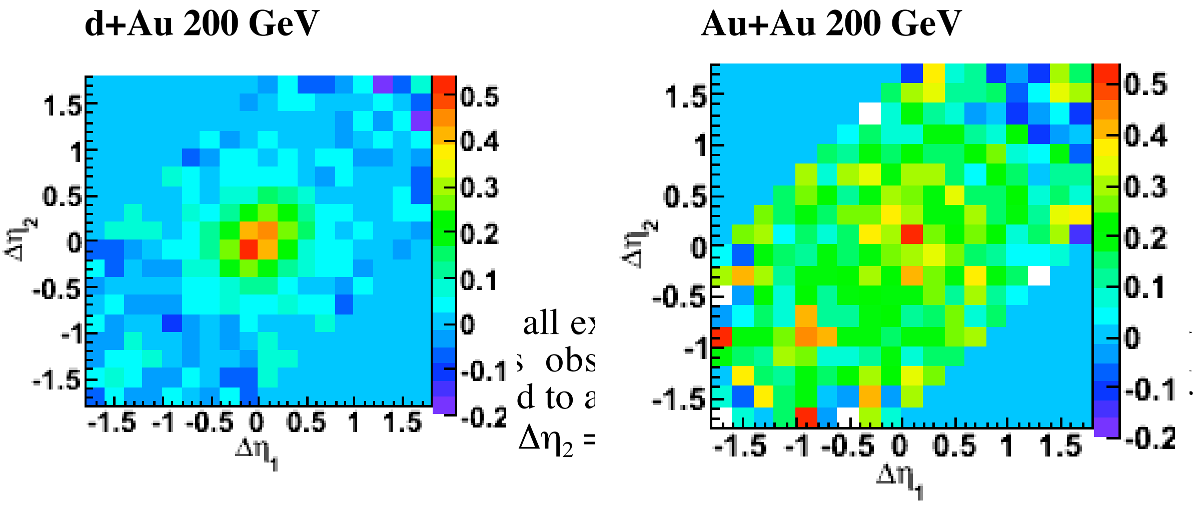
In addition to the above experimental observations in the near side from high p_T triggered di-hadron correlations, STAR has carried out a detailed study of the near side triggered di-hadron correlations with respect to reaction plane. In Au+Au collisions at 200 GeV, it is observed that the ridge yield seems to decrease with increase in the azimuthal angle difference between the trigger particle and the reaction plane. Whereas the jet yield is constant as the function of the angular difference and similar to that observed in d+Au collisions. This observation (shown in Figure 6) can be interpreted as,
strong near-side jet-medium interaction in reaction plane could be possibly generating the sizable ridge and there is minimal near-side jet-medium interactions perpendicular to the reaction plane.

Figure 6 : The yield per trigger for the jet part and ridge part in near-side di-hadron correlations in non-central Au+Au collisions at 200 GeV plotted as a function of angular difference between the trigger particle and the reaction plane. The lines are systematic uncertainties due to uncertainties in the elliptic flow measurements.



STAR also carried out 3-particle correlations in $\Delta\eta-\Delta\eta$ and the results are shown in Figure 7 for minimum bias d+Au collisions (left) and central Au+Au collisions (right) at 200 GeV. The trigger particle p_T range being 3 – 10 GeV/c and associated particle p_T range is between 1 – 3 GeV/c. A clear jet peak is observed in these correlations at $\Delta\eta$, $\Delta\eta \sim 0$ for both d+Au and Au+Au collisions.

Figure 7 : 3-particle correlations in pseudorapidity for small azimuthal anle difference between associated particles and trigger particle for minimum bias d+Au collisions (left panel) and central Au+Au collisions (right panel) at 200 GeV. The central red box indicates the jet-peak structure, observed in both d+Au and Au+Au collisions.



4) Conclusions

1. The theoretically expected differences in energy loss between quarks and gluons are not experimentally observed in the ratios of anti-proton/proton and R_{AA} of pions and protons in the measured p_T range for Au+Au collisions at RHIC.
2. First measurements of γ-hadron correlations in Au+Au collisions at 200 GeV are reported and through comparison with model calculations should be able to provide crucial insights into understanding the mechanism of parton energy loss in the medium formed in heavy ion collisions.
3. Strong jet-medium interactions have been observed in Au+Au collisions at RHIC. Signals of conical emission are observed in central Au+Au collisions at 200 GeV from a detailed analysis based on a 2-component approach.
4. Medium seems to respond to the passage an energetic parton by the formation of the ridge. New observations such as particle ratios in ridge are similar to inclusive, ridge being dominated in-plane and 3-particle correlations in $\Delta\eta$ reflecting a physics scenario of jet fragmentation along with an uniform overall excess of associated particles, should now provide more stringent constraints on the physics mechanism of ridge formation.

5) Outlook

1. First results on di-jet triggered di-hadron correlations were reported. The results revealed features very different from those reported for single high p_T triggered correlations. There is no observation of away-side yield suppression, away-side shape modification or near-side ridge formation for the dijet triggered events. A detailed study of these events with clever changes in trigger and associated particle p_T ranges can provide a controlled

tool to further understand jet-medium interactions in heavy-ion collisions

2. The inferred elliptic flow from events where two high p_T particles lie in the jet cone are much smaller than those lie in the ridge. This study holds the potential to provide further understanding the physics mechanism of ridge formation.
3. STAR also started its first attempts towards full jet reconstruction in heavy ion collisions by reporting an analysis based on multi-hadron cluster triggered correlations. Initial results suggest that single-hadron and multi-hadron triggered correlations associated p_T spectra are similar.

6) References

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